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**Impulse Response of Alternative
Synthetic Apertures for
Subsurface Detection**

James M. Ralston

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PREFACE

This paper was prepared under an IDA Central Research Project entitled “Impulse Response of Synthetic Aperture Radar.”

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I. INTRODUCTION

A. BACKGROUND AND MOTIVATION

The application of radar to the detection and identification of subsurface targets is generally a struggle to distinguish the targets sought from manmade and naturally occurring clutter objects [Refs. 1, 2, 3]. Radar imaging [Ref. 4], which has been under development by many organizations, is one method of achieving this. Several approaches to radar imaging have received attention, including *microwave holography*, *tomography*, and *synthetic aperture radar* (SAR). The common element to all of these is the measurement of the scattered radiation from target and background from several distinct locations in real space, each of which illuminates the scene from a different aspect angle. The data from these measurements is then analyzed by any of several different transforms or inverse methods to arrive at an image of the target+background. The objective of the effort is to obtain a sufficiently detailed image that the targets sought can be distinguished from clutter.

B. ILLUMINATION FUNCTION AND IMPULSE RESPONSE

All of these imaging techniques, whether two- or three-dimensional, fundamentally proceed by illuminating the target region with a wideband waveform from a range of aspect angles or directions. This illumination can be characterized as an *illumination* or *transfer function* defined over a volume of k-space [Ref. 4].

$$p(\vec{k}) = \int d\vec{r} \rho(\vec{r}) \exp(2j\vec{k} \cdot (\vec{R} + \vec{r})) \quad , \quad (1)$$

where \vec{k} is the wavenumber vector defining the direction and frequency of a plane wave, $\rho(\vec{r})$ is the scattering density of the target region being imaged, \vec{R} is the vector between the radar and the object being imaged, and \vec{r} spans the volume of integration. If the scattering density is a spatial impulse $\delta(\vec{r})$, and the vector \vec{R} is set equal to zero, which can be done without loss of generality, Eq. 1 can be inverted to obtain an estimate of the spatial impulse response of the system

$$\hat{\rho}(\vec{r}) = \int_k d\vec{k} \exp(-2j\vec{k} \cdot \vec{r}) \cong \frac{1}{N} \sum_k \exp(-2j\vec{k} \cdot \vec{r}) \quad , \quad (2)$$

where the summation is taken over the set of \vec{k} -vectors used to illuminate the target region, and N is a suitable normalization factor. This estimate is equivalent to the impulse response of the system under consideration.

C. CROSS-RANGE RESOLUTION AND RANGE OF ASPECT ANGLE

Equation 2 is sufficiently general to apply to all cases of microwave imaging. A useful expression for the cross-range spatial resolution, Δx , of an imaging system is

$$\Delta x = \frac{\lambda}{4 \sin(\Delta \theta / 2)} \cong \frac{\lambda}{2 \cdot \Delta \theta} , \quad (3)$$

where λ is the wavelength of the illumination and $\Delta \theta$ is the angle subtended by the synthetic aperture at the imaging point. Equation 3 states that the resolution in the direction perpendicular to an illumination direction is inversely proportional to the apparent angular extent of the synthetic aperture normal to the illumination axis. When the imaging point is below the surface, however, the angle is compressed by surface refraction in the following way:

By Snell's law:

$$n_1 \sin(\theta_i) = n_2 \sin(\theta_r) ; \quad (4)$$

for angle differentials:

$$\frac{d\theta_r}{d\theta_i} = \frac{n_1}{n_2} \cdot \frac{\cos(\theta_i)}{\cos(\theta_r)} , \quad (5)$$

where n_1 and n_2 are the refractive indices for the two media and θ_i and θ_r are the angles between the incident and refracted rays and the surface normal (see Figure 1). For incident angles, θ_i , near grazing, this ratio becomes very small. As a consequence, the apparent angle subtended by the synthetic aperture becomes very small, and the resolution in the direction normal to the illumination direction is severely degraded. This effect will be apparent in the impulse response examples to follow.

D. OBJECTIVE AND LIMITATIONS OF ANALYSIS

The objective of the analysis described here is to allow a rapid assessment of the impulse response or spatial resolution that can be anticipated from a wide range of possible schemes for subsurface target illumination. The approach is subject to several approximations and limitations which must be considered when interpreting the results and generalizing the method to additional cases:

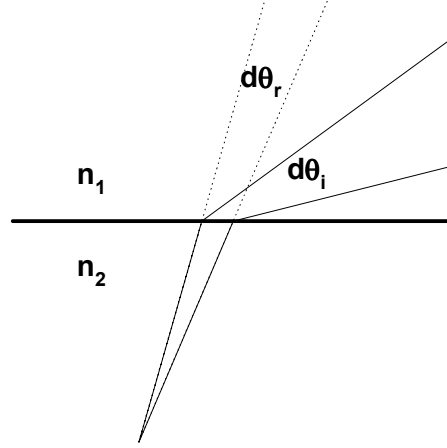


Figure 1. Effect of Surface Refraction Is to Compress Angular Spread of Ray Bundles

- *Soil properties*—We assume that the soil is perfectly homogeneous. In practical systems, soil inhomogeneity will strongly affect the image quality obtained [Refs. 5, 6]. Soil losses and their frequency dependence are neglected.
- *Surface properties*—The soil surface is assumed to be perfectly planar. We account for Snell's refraction law but not for reflectance losses or their frequency dependence.
- *Target-environment interaction*—Scattering effects within the target (resonance) and between target and surface are not considered. Likewise, multiple surface reflections are not accounted for.
- *Parallax and near-field effects*—Plane-wave illumination is assumed. We assume that the point at which illumination rays pass through the soil is (nearly) the same for all points in the synthetic aperture. The effect of surface refraction is included by transforming the free-space incident angle to the refracted angle in the medium according to Eq. 4.
- *Impulse response*—Because the impulse response is computed within the soil medium, we assume that the burial depth is greater than the depth resolution of the system. The surface does not appear in the plots of impulse response.
- *Antenna beamwidth*—Rolloff of the primary element's antenna pattern is not considered.
- *Sidelobes and aperture weighting*—There are many ways in which target illumination can be apodized to minimize sidelobe effects and account for the frequency dependence of propagation losses. For this analysis, however, we consider only a direct unweighted summation of the points in k-space representing the target illumination. This method will yield a mainlobe width close to the best (minimum) that could be achieved, but not necessarily the

best sidelobes. For this reason we plot the impulse response on a linear scale to emphasize mainlobe features.

In most cases of interest the results of this method will be good approximations to more exact methods, while the speed and efficiency afforded allow many different cases to be quickly analyzed. Besides comparing the impulse response of a wide range of different aperture configurations, we can evaluate the change in impulse response for a given synthetic aperture as the focused pixel is moved to various positions in the radar field of regard.

2. SYNTHETIC APERTURE ALTERNATIVES

The application of radar to the systematic detection of subsurface targets, particularly mines, has led to the development of a wide range of alternative systems for creating synthetic apertures for target illumination. Early diagnostic systems [Refs. 2, 3] scanned a rectangular horizontal aperture directly above the region of interest. Later geometries used vertically oriented rectangular apertures to examine buried regions located in front of the radar. Still more recent systems have attempted to perform subsurface imaging with horizontal apertures substantially offset from the region of interest in a strongly squinted geometry. The latter two approaches are particularly appropriate for forward-looking mine detection since they could lead to mine declaration and location before the search vehicle passes above the possible target.

Each of the subsequent four-part figures (Figures 2–12) follows a common plan. In (A) we plot first the real-space region scanned by the synthetic aperture, with the point of desired image focus (+) shown for reference. We then (B) show the k-space transfer function that would result from illuminating the focal point with a radar bandwidth of 500–1,500 MHz from each of the points in the apertures. We then plot (C), a one-dimensional trace of the impulse response in the cross-track direction. This subfigure also summarizes the conditions pertaining to the entire figure. Finally, we show (D), a two-dimensional section of the impulse response in a vertical plane through the focal point. This allows the shape of the impulse response lobe to be shown and also shows the effect of surface refraction in causing a loss of resolution in the direction normal to that of primary illumination.

Figure 2 shows the impulse response associated with a “rail-SAR” of the type used by ERIM and Lincoln Laboratory [Ref. 7] for the measurement of both surface and subsurface targets. In this case Figure 2A shows that the synthetic aperture comprises a region 10 m wide by 5 m high, centered 5 m above the surface. Data collected from this aperture are used to focus an image pixel on the surface at a range of 20 m from the aperture. From the standpoint of this pixel, the k-space illumination function is shown in Figure 2B. Figure 2C is a one-dimensional transverse cross-range trace through the amplitude of the impulse response. Figure 2D is a two-dimensional contour plot of the impulse response amplitude in the vertical plane whose horizontal axis is the downrange

direction from the radar toward the focused pixel. In this and subsequent figures, the five contour lines correspond to the peak of the impulse response times (0.9, 0.7, 0.5, 0.3, 0.1). Figure 3 is the corresponding case in which the focused pixel is below the surface, so that refraction has compressed the aspect angle range of the target. Comparison of Figure 2B with 3B shows how the k-space spectral support region has been reoriented, extended in length but also compressed in the vertical plane. Cross-range resolution is unchanged in this geometry since the wave vector increase in the dense medium is offset by the angle compression due to refraction. In the elevation plane, Figure 3D, the effect of refraction in the dense medium is clear. Comparison with Figure 2D shows that the impulse response has been rotated because of the larger angle of refraction, thinned in the direction normal to propagation by the larger wave vectors, but extended dramatically in the perpendicular direction due to angular compression.

Figures 4–7 show a different synthetic aperture geometry, one typical of many ground-penetrating radars (GPRs) designed for forward-looking mine detection [Ref. 8]. A typical configuration of these systems is a horizontal antenna aperture (either real or synthetic) extending the width of the vehicle. As the vehicle moves down the road, radar sweeps in successive locations create a synthetic aperture in a horizontal plane. Because the antennas are directed forward, this amounts to a strongly squinted synthetic aperture that can be focused to surface and subsurface points at some distance in front of the vehicle. Figure 4 corresponds to a 4-m wide antenna array at 1 m above ground level (AGL), where it might be placed on a rack projecting in front of the vehicle. As the vehicle moves, this array forms a horizontal rectangular (4 m by 10 m) synthetic aperture focused 15 m in front of the array. Figure 4A shows the real-space aperture and Figure 4B the corresponding k-space support after refraction. Figure 4D shows that despite the substantial increase in wave vector below the surface, angle compression has essentially negated any transverse resolution in the vertical plane.

If true three-dimensional resolution is required, system designers have the option of increasing the height of the antenna array. Figure 5 shows the effect of increasing aperture height to 6 m AGL. This provides a slight but measurable improvement in vertical-plane resolution. Figures 6 and 7 show the effect of moving the processed point closer to the end of the aperture. This improves cross-range resolution in both the vertical and horizontal planes, although good three-dimensional resolution is only approached when the focused pixel is adjacent to the synthetic aperture, that is, when the standoff distance is near zero.

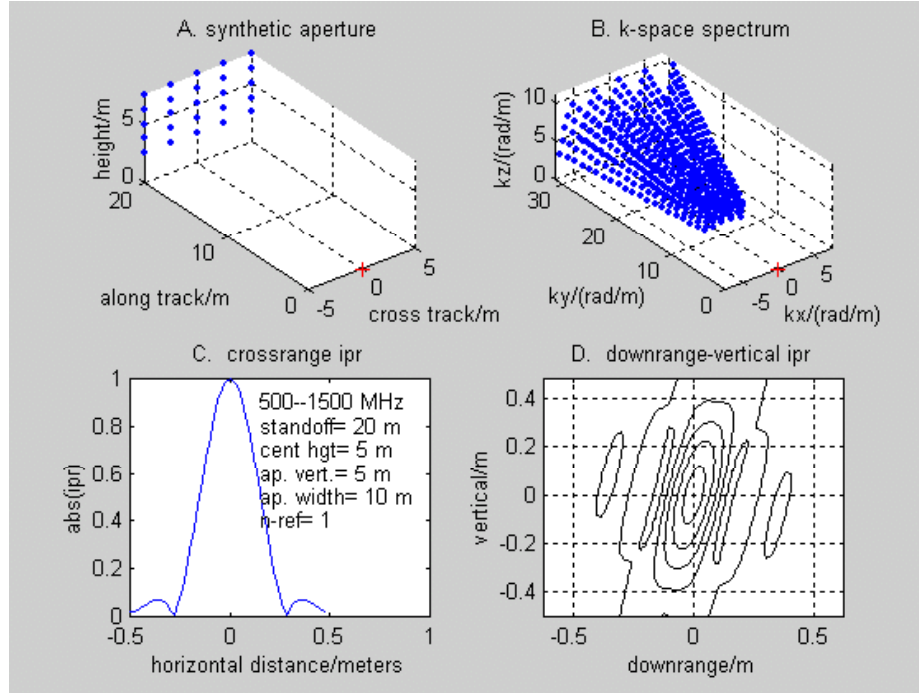


Figure 2. Rail SAR Impulse Response. Focused point is in air. Contours in D. are at 0.9, 0.7, 0.5, 0.3, and 0.1 times peak of impulse response magnitude (volts).

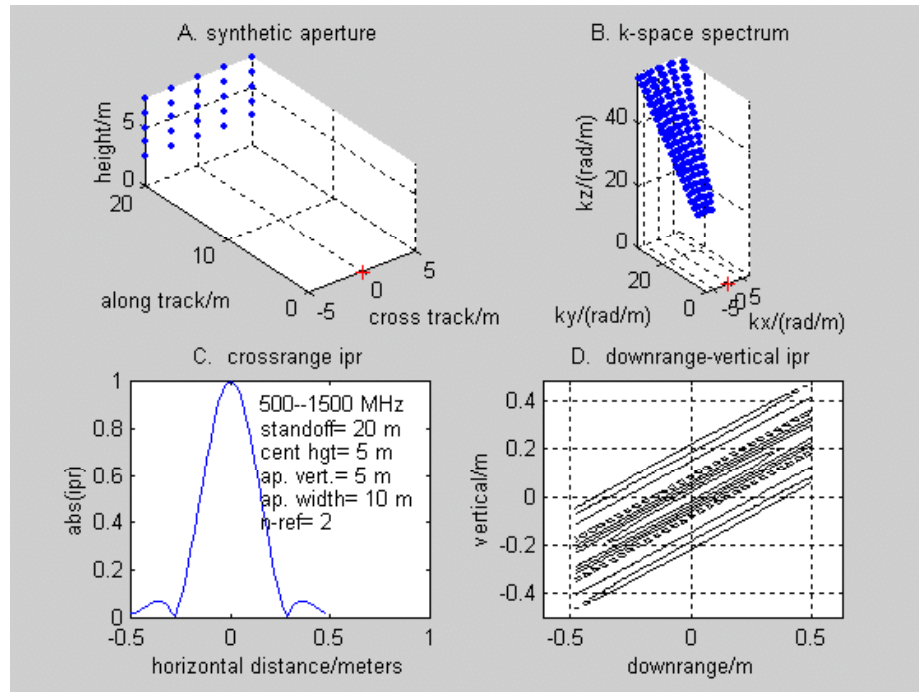


Figure 3. Rail SAR Focused in Dense ($n = 2$) Medium. Note the compression of ray bundles and loss of transverse resolution in the elevation plane.

The conclusion from Figures 4–7 is that it will be very difficult for forward-looking GPR systems to achieve both significant subsurface vertical resolution and good

standoff range. For mine detection, this may be acceptable, provided significant sub-surface resolution is not needed to reject clutter.

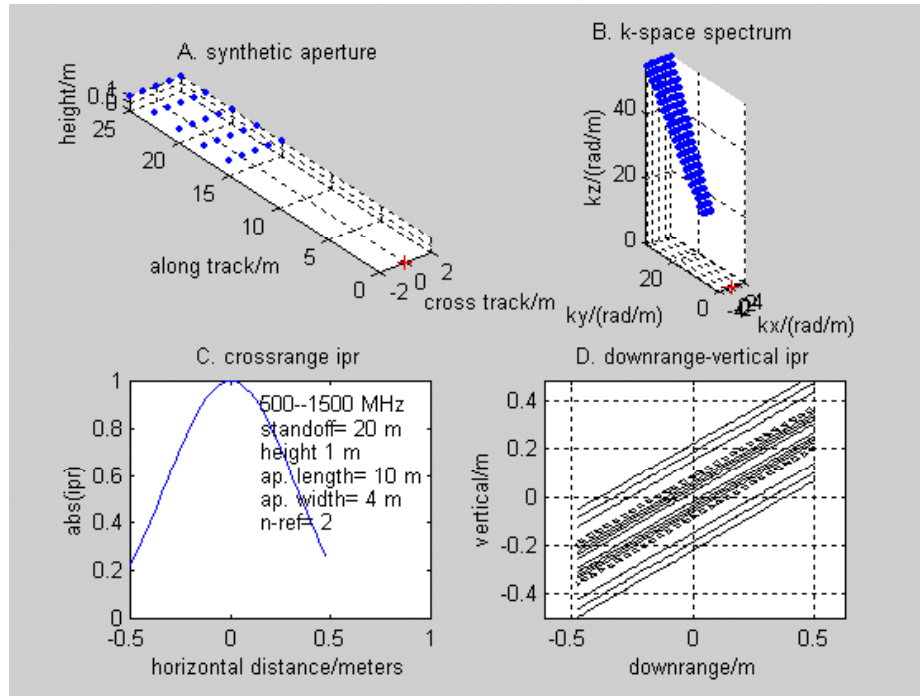


Figure 4. Forming a Synthetic Aperture by Forward Motion of a Transverse Linear Array. Near-grazing angle leads to total compression of angular spread and loss of resolution.

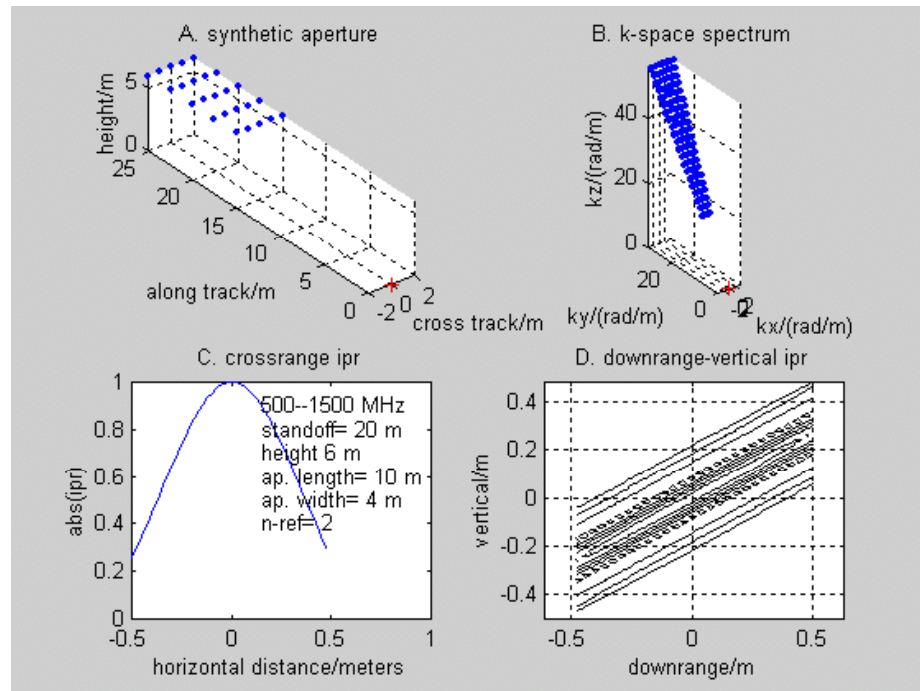


Figure 5. Raising the Antenna Array Provides a Larger Grazing Angle. Transverse vertical plane resolution is slightly improved.

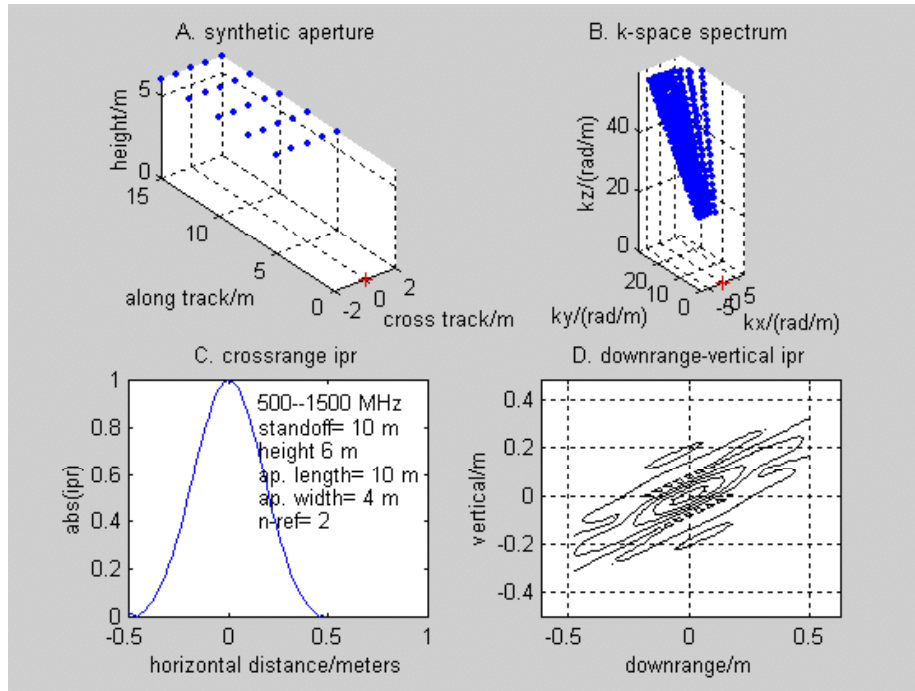


Figure 6. Both Raising the Antenna and Forming an Image Closer to the Synthetic Aperture Shows Significant Improvement in Vertical Plane Resolution

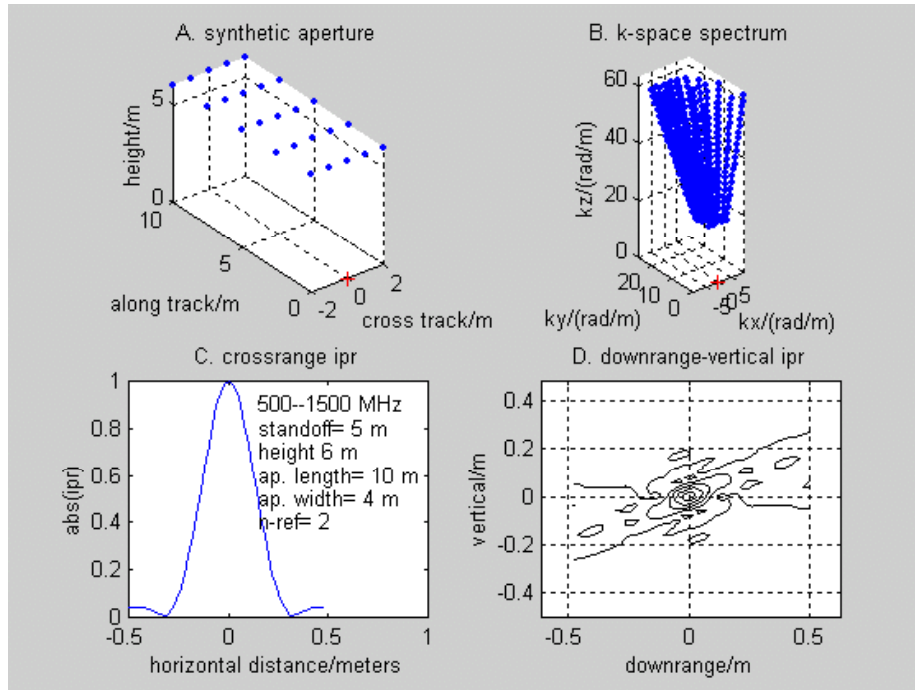


Figure 7. The Extreme Case Forms the Image at the Edge of the Synthetic Aperture. This provides the best resolution but at minimal standoff range.

A different synthetic aperture configuration, which has been widely used in diagnostic GPR, is a rectangle placed directly over the region of interest. This maximizes the symmetry of the k-space transfer function support and also provides what is, in principle, the largest support affordable in a given frequency band. In Figure 8 we analyze the response of a 2-m square aperture centered above the pixel of interest. In this case the focal point is assumed to be in free-space ($n = 1$). Note from Figure 8D that the downrange resolution is about twice as fine as the vertical resolution. This is consistent with Figure 8B, which shows that the downrange and cross-range support of the transfer function is about twice its vertical extent. The geometry is the same in Figure 9, except that the focal point is in a soil medium ($n = 2$). Note that while the vertical resolution is twice as fine as in Figure 8D, transverse (horizontal) resolution is the same as in the previous free-space case. This result is a consequence of Eqs. 3 and 4. Immersing the focal point in the medium of index, n , compresses $\sin(\Delta\theta/2)$ and λ by the same factor of n , leaving transverse resolution unchanged. Figure 10 is similar to Figure 9, except that the focused pixel is offset 0.7 m from the center of the aperture. The effect of asymmetric illumination (Figure 10D) is to change the sidelobe structure without significantly affecting mainlobe resolution. This suggests that a single synthetic aperture position can provide a large field of regard for imaging, without unacceptable loss of image quality.

Because good resolution in three dimensions arises not only from wideband illumination but also from the widest possible range of diversity in illumination direction, it is worthwhile to consider the most efficient aperture shapes from the standpoint of maximizing resolution from the smallest number of measurement points. One possible choice for an efficient synthetic aperture is a circular trajectory [Ref. 9], as shown in Figure 11A. This corresponds to moving a radar 20 m AGL in a circle of 20-m radius about the focused pixel. Figure 11B shows the corresponding k-space support for subsurface focusing. Note the overall similarity in the support volume between this case and that of the filled square aperture described in Figure 9B. Surface refraction tends not only to move the incidence angle of the illumination rays closer to the vertical, but also to compress their range of variation. As a consequence, there is less difference in k-space support between the filled square and hollow circular apertures than would at first be expected. This is further confirmed by comparison of the impulse responses of the two cases (Figures 9D and 11D). Despite the apparent differences in illumination, the mainlobe shapes of the impulse responses are very similar.

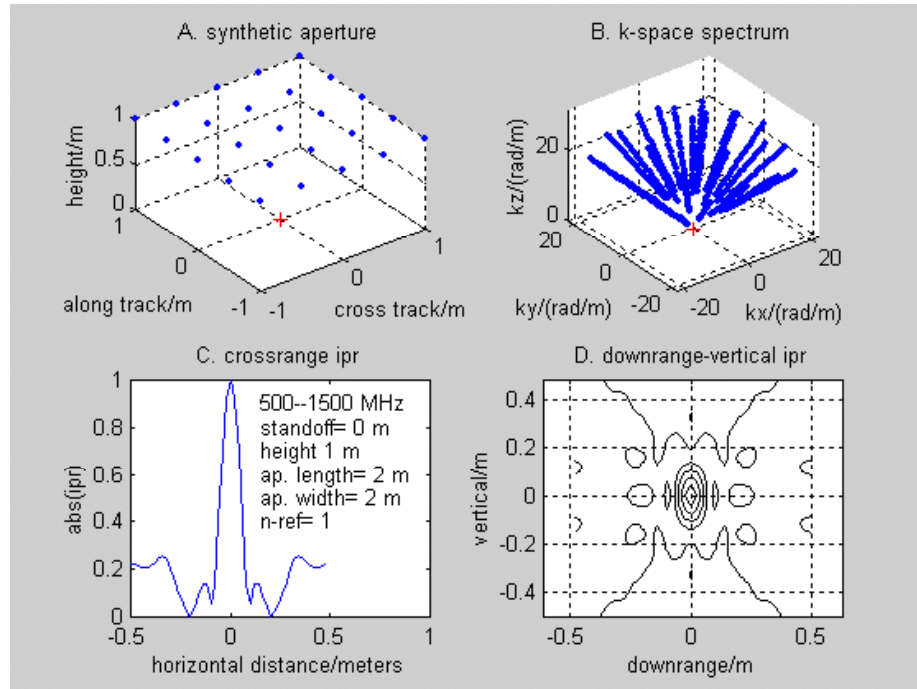


Figure 8. Typical Geometry for Tomographic or Holographic Reconstruction.
This pixel is imaged in air ($n=1$).

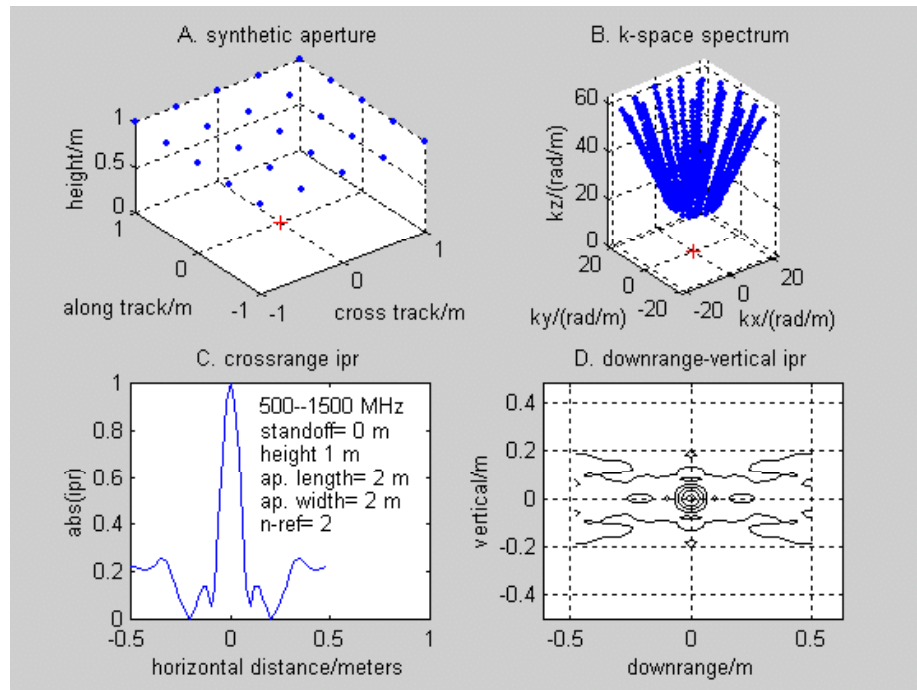


Figure 9. Same Geometry as Figure 8, but Pixel Is Focused in Dense Medium. Vertical resolution is improved but transverse is unchanged.

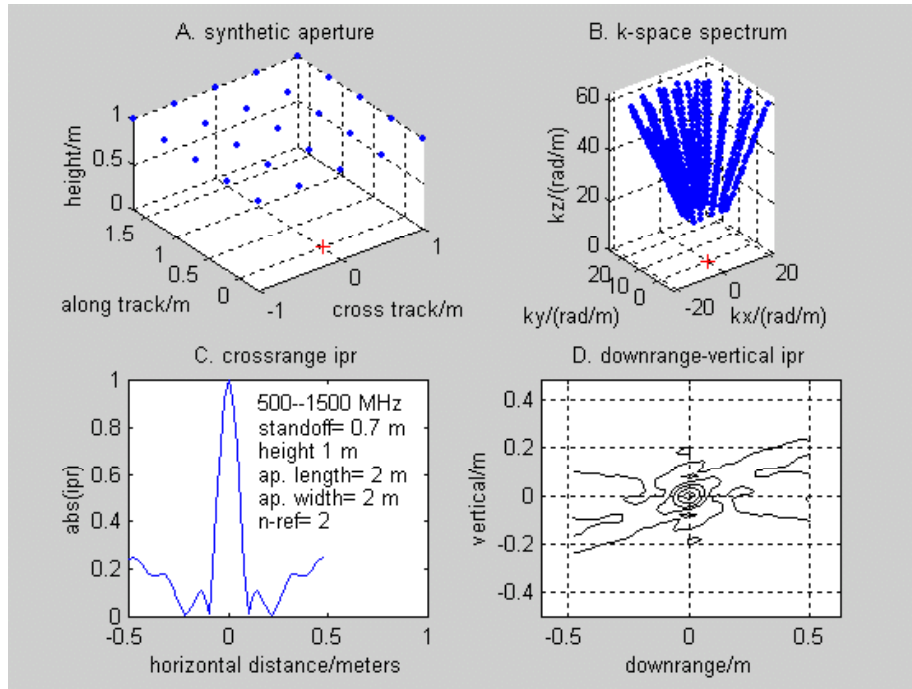


Figure 10. Focusing an Off-Center Point Leads to Some Distortion of Impulse Response, but Volume of Resolution Cell Is Negligibly Affected

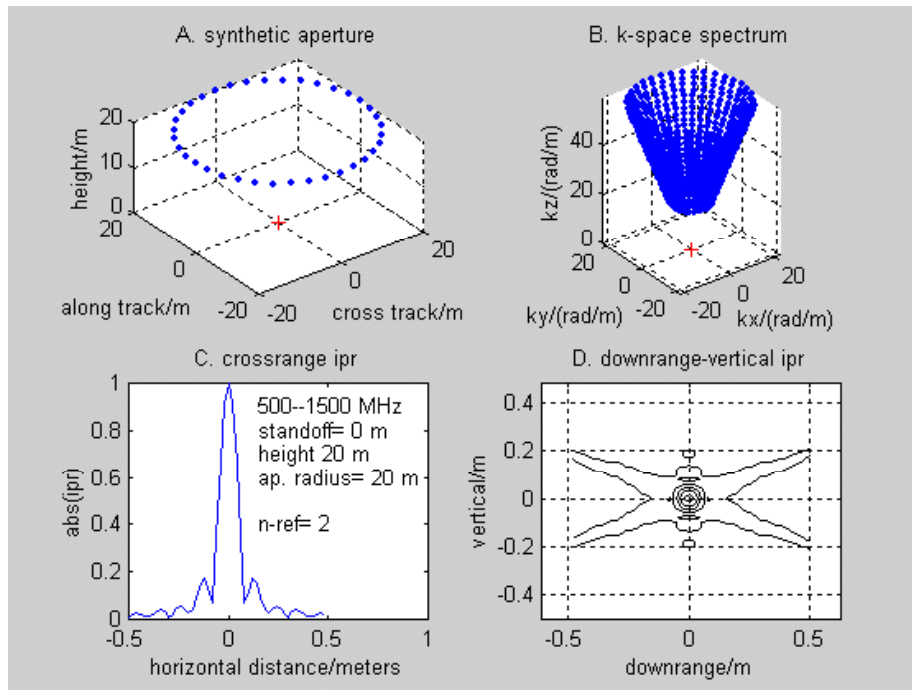


Figure 11. The Empty-Circle Aperture Provides Similar Illumination Angle Diversity to Figure 9. Note similarity of resolution cell.

The final point to be made is that the circular aperture is similarly robust with respect to off-center focusing. In Figure 12 we consider the case of a focused pixel 10 m from the aperture center. As we saw for the case of the filled square aperture (Figures 9 and 10), although the shape of the impulse response mainlobe and sidelobe structure is changed, the basic resolution remains the same as for the centered case.

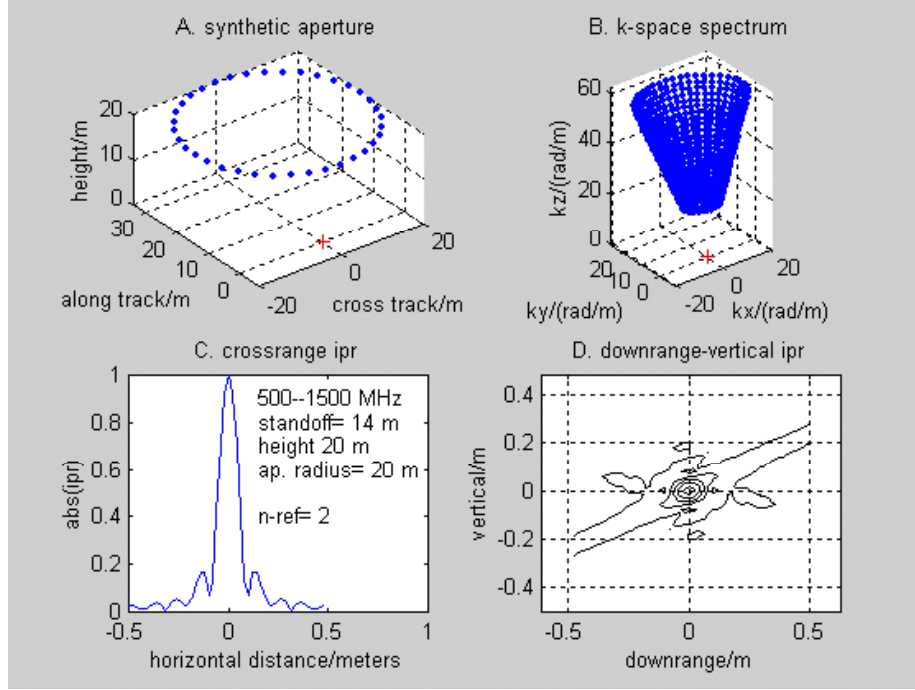


Figure 12. Focusing an Off-Center Point Changes Sidelobe Structure with Negligible Impact to Mainlobe Resolution

3. CONCLUSIONS

Ground-penetrating radar is an important technology for subsurface target detection, with particular application to both mine and UXO detection. Although it has been in development for many decades, it is clear that much work remains to be done. Specific designs for imaging subsurface radar have been proposed by many organizations, and several have undergone significant system development. Before making major design commitments, however, it is desirable to be able to estimate the anticipated resolution of a given system concept based on a first-order map of the k-space illumination support its geometry will afford. The techniques described in this paper allow a system designer to explore the effect of variations in system mechanical design on radar resolution. In addition, we are able to estimate the field of regard which may be focused from a single aperture without excessive degradation of image quality. Finally, it is clear that the angular spread of ray bundles is severely compressed by surface refraction, particularly for near-grazing incidence, with consequent impact on subsurface resolution.

4. REFERENCES

1. Daniels, D.J., "Surface Penetrating Radar," IEE, 1996.
2. Richards, P.J., and A.P. Anderson, *Proc. 8th European Microwave Conf.*, 1978.
3. Daniels, D.J., D.J. Gunton, and H.F. Scott, *IEE Proc.* 135, Pt. F, No. 4, August 1988.
4. Sullivan, R.J., *Microwave Radar: Imaging and Advanced Concepts*, Norwood, Mass., Artech House, 2000.
5. Nguyen, L., K. Kappra, D. Wong, M. Ressler, and J. Sichina, "Mine Detection Performance in Different Soil Conditions using Data from an Ultra-Wideband Area Surveillance Radar," *Proc. SPIE*, v. 3710, p. 930, April 1999.
6. Rappaport, C., S. Winton, D. Jin, and L. Siegel, "Modeling the Effects of Non-Uniform Soil Moisture on Detection Efficiency of Mine-like Objects with GPR," *Proc. SPIE*, v. 3710, p. 979, April 1999.
7. Blejer, D., C. Frost, and S. Scarborough, "SAR Imaging of Minelike Targets over an Ultra-Wide Bandwidth," *Proc. SPIE*, v. 2496, p. 54, April 1995.
8. Kositsky, J., and P. Milanfar, "A Forward-Looking High Resolution GPR System," *Proc. SPIE*, v. 3710, p. 1052, April 1999.
9. Falconer, D., and G. Moussally, "Tomographic Imaging of Radar Data Collected on a Circular Flight Path About a Three-Dimensional Target Zone," SPIE Aerosense Symposium, Orlando, Fla., 19 April 1995.

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13. ABSTRACT (Maximum 180 words) In this paper, we examine the three-dimensional spatial impulse responses associated with alternative geometries for synthetic aperture data collection. Several alternative radar geometries corresponding to both forward-looking (stand-off) and down-looking configurations have been chosen for examination. The ultimate limiting factor on the impulse response of a synthetic aperture radar (SAR) is set by the aperture itself, which may be defined as a set of points in k-space representing both the frequency (or wavenumber) and direction of radar illumination. This k-space illumination function is largely controlled by the mechanical geometry and bandwidth of the radar system employed. Several examples of this technique are given, as applied to the SAR apertures associated with forward-looking, standoff GPR on moving vehicles; the "billboard" shaped aperture available with rail- or boom-SAR systems; a circular aperture; and the down-looking X-Y scanned aperture associated with holographic data reconstruction.				
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